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Walkaway DAS VSP simultaneously acquired between two deep wells

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Summary

The initial findings of a simultaneous recording of dual-well distributed-acoustic-sensing VSP acquisition demonstrates the ability of on-tubing fibre to record high-quality seismic signals down to about 4 km depth. Each shot was recorded by two fibres deployed in wells that are 1.5 km apart. A dual-fibre interrogator enables the efficient recording of a high-channel-count walkaway VSP dataset suitable for robust velocity model building. Even with high-quality casing cementation, DAS records exhibited reduced sensitivity/coupling in the shallower section requiring low-pass filtering for robust first-break picking. The corridor stacks at the two wells show an excellent tie to surface seismic and agree with the ZVSP geophone corridor stack at one of the wells. A massive ensemble of first-arrival picks enabled multi-offset traveltime inversion to reconstruct a reliable profile approaching sonic-log resolution and overcome the lower sensitivity of DAS measurement at higher angles.

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Introduction

Distributed acoustic sensing (DAS) technology has recently become an inexpensive alternative to conventional vertical seismic profiling (VSP) wireline acquisitions (Zhan, 2020). DAS utilizes optical fibre-optic cables as a sensing array to capture seismic signals as opposed to three-component geophones used in conventional VSP surveys. Downhole wireline geophones are conventionally spaced at 15 m, and the array's length is limited to a few hundred meters, which is typically moved several times to cover the entire well (Titov et al., 2021). In contrast, fibre-optic cables are often installed in wellbores to monitor pressure and temperature of the well for production purposes covering the entire extent of the well (Fitzel et al., 2015). These pre-installed cables can also be used to record VSP datasets in a non-intrusive borehole operation providing a seismic vibrator and recording equipment.

Numerous DAS VSP field tests have been conducted for subsurface imaging and monitoring using various VSP acquisition geometries, and cable conveyance methods (e.g., on-tubing, behind the casing, wireline, etc.) (Hartog et al., 2014, Mateeva et al., 2014, Parker et al., 2014). In this field trial, we have acquired a simultaneous dual-well DAS walkaway VSP dataset with pre-installed fibre-optic cables on production tubes. Data quality assessment, velocity model building and seismic reflectivity imaging are the main objectives of acquiring this dual-DAS VSP survey. We compare our results from this field experiment with legacy conventional geophone VSP and sonic data available in one of the wells.

DAS-VSP Data acquisition

We utilized pre-installed fibre-optic cables in two adjacent non-flowing wells in a desert environment as receiver arrays to conduct the VSP survey. A dual-fibre integration box was used to connect the cables from both wells enabling the acquisition of densely sampled walkaway VSP data. As a result, this has saved the substantial cost of acquiring two separate walkway lines, one for each well. The two wells are separated by about 1.5 km, each with a total depth of around 4 km. Both wells are equipped with pre-installed fibre-optic cables clamped on production tubes.

The gauge length (GL), the fibre length over which the recorded signal is optically averaged (Dean et al., 2017; Hartog, 2017), is a key parameter in DAS acquisition. In this experiment, we set GL to 24 to maximize the signal-to-noise ratio (SNR) in order to reveal the signal at 4 km depth. We also set the receiver spacing to 6.4 m. Such dense sampling enables robust signal processing steps such as wavefield separation and first-break picking, and minimizes spatial aliasing. Two vibrators executing 16 sweeps at each shot location were used as a seismic source with shot-point spacing of 12.5 m.

Figure 1a shows the geometry of the simultaneous dual-well acquisition, with the red dots denoting the 293 shot points and the yellow dots representing the receiver stations along the DAS cables (639 in well A and 630 in well B). The wells are nearly vertical, with well A showing high deviation angles up to 26 degrees at deeper levels. Following shot-point stacking in the field, we retrieved over 370,000 traces, an order of magnitude larger than conventional geophone walkaway VSP acquisition with similar geometries.

DAS-VSP Data processing and analysis

We present and discuss in this section the initial results of the recently acquired dual-well DAS VSP dataset. Figure 1b shows a common-shot gather simultaneously recorded in two wells. This gather represent a near-offset shot for Well A while it is a far-offset one with respect to Well B. In addition, the integration box was closer to well A and we used an extension cable, of about 1.5 km length, to connect the integrator to well B. As a result, the estimated SNR is about 5 dB lower in well B than in well A when comparing shot records with similar offsets from the wells.

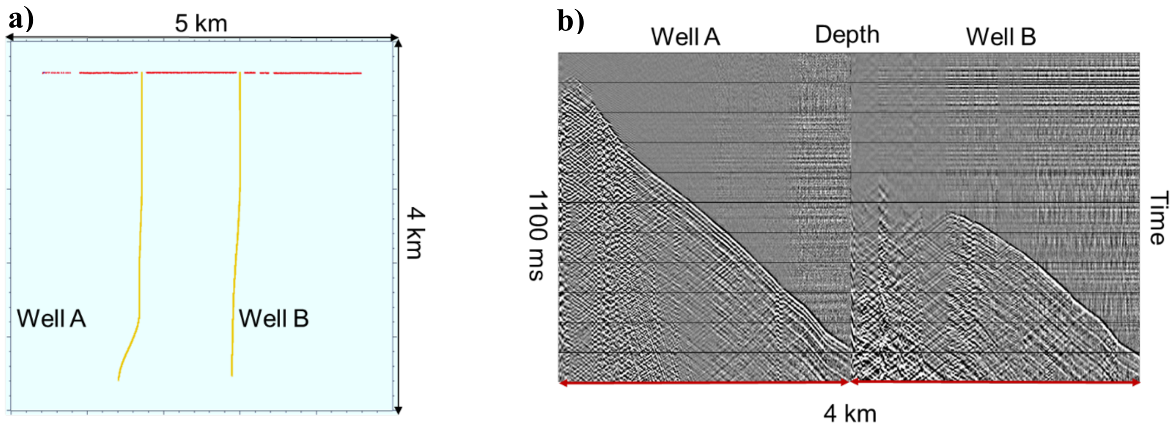

Figure 1 *Dual-well acquisition: a) the acquisition geometry with receivers denoted by the yellow dots, and the red dots represent the shot points. b) A typical common shot gather recorded simultaneously at the two wells shows high-fidelity DAS data at near and far offset down to 4 km depth.*

We applied a processing workflow tailored for DAS VSP data. To facilitate robust first-break picking, we applied a low-pass filter up to 30 Hz to the data in order to enhance the first arrival waveforms, especially in the shallow section of the well. This can be clearly seen in Figure 2a, where the data showed reliable shallow first arrival events, marked by the red circle, compared with the full bandwidth data (Figure 2b) at well A.

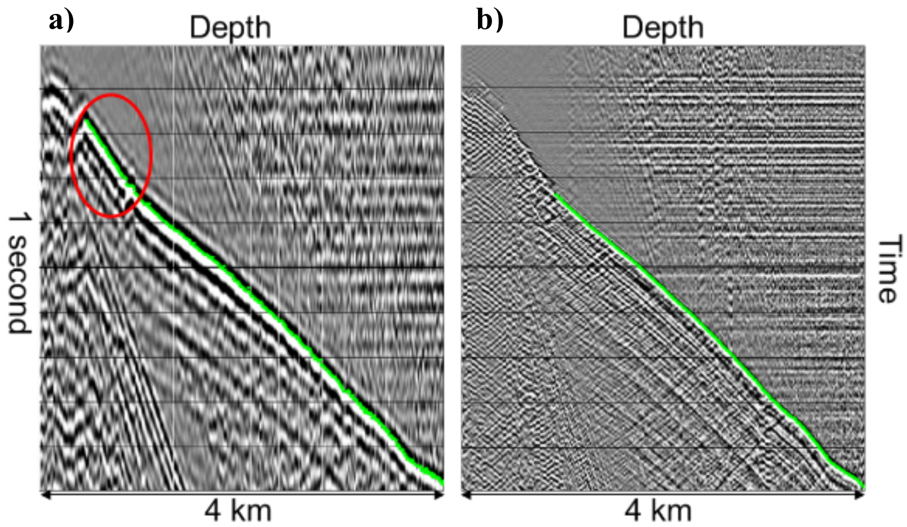

Figure 2 *Low-pass filtering effect: a) the low-frequency filtered data allows extending the picks to as shallow as 500 m depth denoted by the red circle, compared with b) the full bandwidth data.*

Upgoing and downgoing wavefield separation is restricted to few methods including FK and median filtering since the recorded DAS VSP data is a single-component strain measurement along the fibre (Sayed and Stewart, 2020). We obtained a corridor stack from DAS zero-offset VSP (ZVSP) data at well A plotted in Figure 3a. The corridor stack resembles closely the one obtained from conventional ZVSP geophone data. In addition, we performed a seismic-to-well tie as shown in the figure that yielded a notable correlation to both corridor stacks obtained from the DAS ZVSP data in both well A and B.

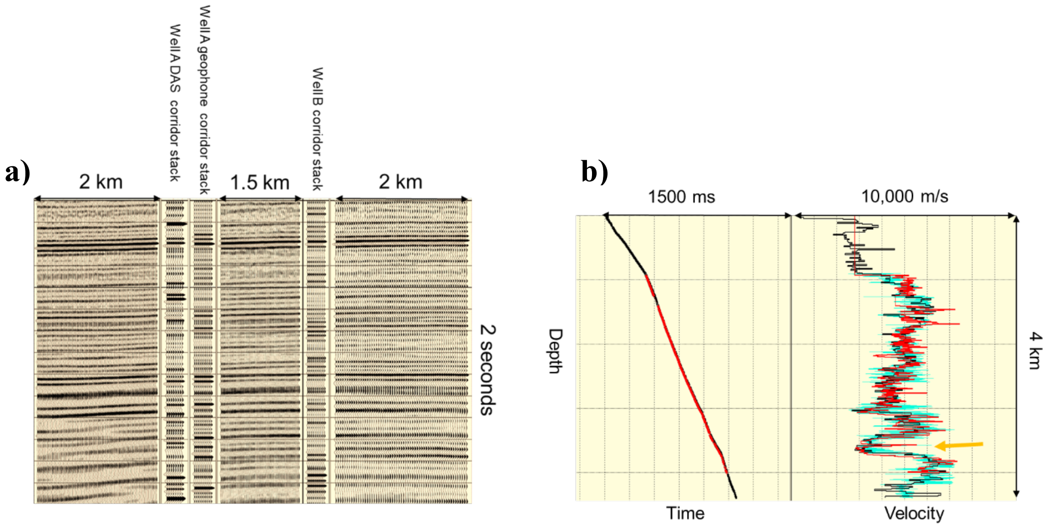

Figure 3 *a) The corridor stacks at wells A and B strongly correlate with the surface seismic section in between and away from the wells. It also ties with the geophone data at well A. b) velocity profiles and time-depth curves: the DAS ZVSP velocity profile (red curve) at well B remarkably agrees with the P-wave sonic log (light blue curve) and the geophone-derived wave speed profile (black curve). The yellow arrow denotes a streak of thin high-velocity layer outlined by DAS measurement.*

The first-arrival traveltime picking of DAS ZVSP data at well B yields a high-resolution *P*-wave velocity profile as shown in Figure 3b. The red curve represents the velocity profile from ZVSP DAS data, the velocity obtained from sonic log is in light blue, and the black curve represents the legacy profile reconstructed using the geophone ZVSP data. It also shows that the velocity profile obtained from DAS ZVSP data is highly comparable to velocity profiles obtained from both legacy geophone ZVSP and sonic log. In addition, a streak of high-velocity sediments was captured by the DAS measurement. The presence of this streak can be confirmed by sonic log (yellow arrow) and it was not delineated accurately by the legacy data mainly due to the large geophone spacing. Therefore, high-resolution subsurface geological models can potentially be obtained from DAS VSP measurements.

Similarly, Figure 4a shows the *P*-wave velocity profiles using the ZVSP DAS at well A (green curve) and legacy geophone velocity profile in the nearby well B (black curves) with their associated time to depth curves. The agreement between the two velocity profiles is remarkable demonstrating the robustness of the DAS first arrival picks for this well. However, as the well deviation of the deeper section is high, the sensitivity of the DAS measurement to the direct arrival from the ZVSP shot degrades; hence, the quality of the traveltime picks worsens. As a result, the obtained velocity profile in this section of the well diverges from the stable geophone profile, as denoted by the blue arrow in the figure.

To rectify this oscillatory effect of the velocity profile in the deviated section of well A, we make use of the large ensembles of first-arrival traveltimes from 293 shots and 639 receivers. Over 140,000 picks were used for a 1D (i.e., laterally-invariant) traveltime inversion. We used a starting velocity model consisting of five layers. Figure 4b shows the inverted velocity profile (red curve) and its associated time-depth curve compared with the geophone velocity profile (black curve and picks). It shows that the inverted velocity profile matches closely the geophone one in the highly deviated section of well A. This result demonstrates that multi-offset inversion of the walkaway traveltime picks can yield a robust velocity profile despite degraded data quality in the deviated section of the well.

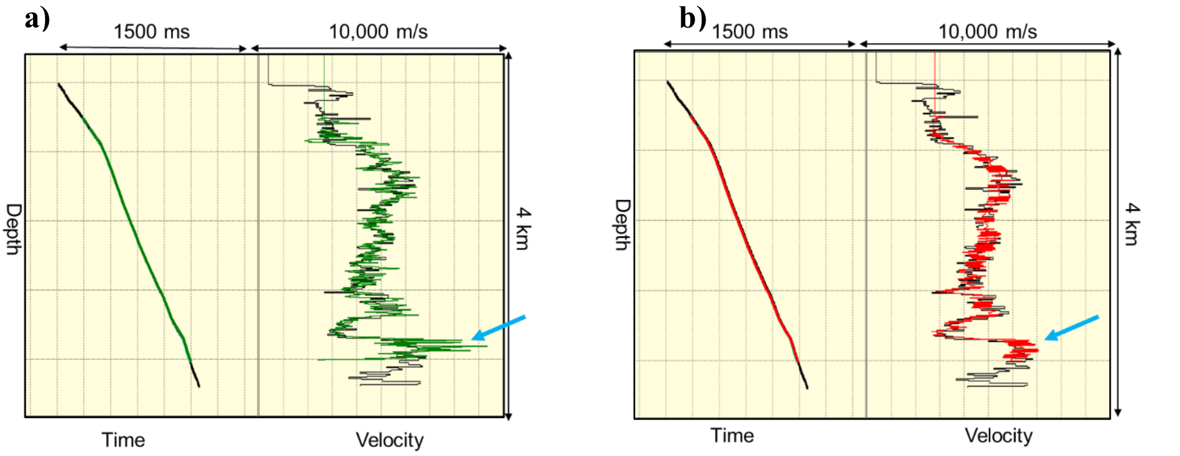

Figure 4 *DAS ZVSP velocity profiles and time depth-curves: a) the DAS velocity profile and time-depth curve in well A (green curve and picks) agrees with the geophone data (black curve and picks) at nearby well B but shows oscillatory velocities in the deviated section. b) Tomographic multi-offset inversion with lateral homogeneity constraint uses large ensembles of picks and yields a more robust velocity profile and time-depth curve, especially in the deviated section denoted by the blue arrows.*

Conclusions

We present the initial findings of a simultaneous dual-well DAS acquisition using pre-installed on-tubing fibres in two adjacent non-flowing wells in a desert environment. The obtained DAS VSP data using this type of fibre installation and conveyance is of high quality down to 4 km depth. The SNR of the records at well B shows a drop of about 5 dB compared to well A since well B is connected to the interrogation box using a long extension cable. We concluded that low-frequency filtering was an essential processing step to enable robust first-break picking as shallow as 500 m. The obtained DAS corridor stacks at the two wells tie well with the surface seismic sections and the legacy geophone VSP corridor stack. The DAS velocity profile at well B demonstrates the potential to reconstruct a high-resolution *P*-wave velocity model conforming with the sonic log. Also, the multi-offset laterally invariant inversion at well A shows that the large ensemble of DAS walkaway traveltime picks can be used to invert for a robust and stable velocity profile in spite of the low DAS sensitivity in the deviated section of the well.

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